CONFIDENTIAL

DEVENCO INCORPORATED

RO #2 : 12/15/53 - 4/1/54

PROGRESS REPORT

(Covering period of Dec. 15, 1953 to April 1, 1954)

ON

RESEARCH ORDER NO. 2

CONTRACT NO. RD-51-SA

**

PROJECT NO. 1353

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PROJECT NO. 1353

I. PURPOSE:

For a description of the purpose of this project reference should be made to Contract No. RD-51-SA and the original proposal outline of proposed scope.

II. ABSTRACT:

1. The effectiveness of shielded microphone cable and "twisted pair" has been investigated with regard to reduction of electric and magnetic fields.

2. Coil sensitivity requirements are re-evaluated in terms of ambient noise and shielding ratio.

3. An electrostatic detection system that is moderately effective with "crystal type" transducers is described.

III. REPORT:

The magnetic field detection system described in the previous progress report was used to experimentally determine the shielding effectiveness of shielded cable, and "twisted pair". The system, as drawn on p.2, was used to determine how great a reduction in the external magnetic field due to a current-carrying conductor can be achieved by shielding.

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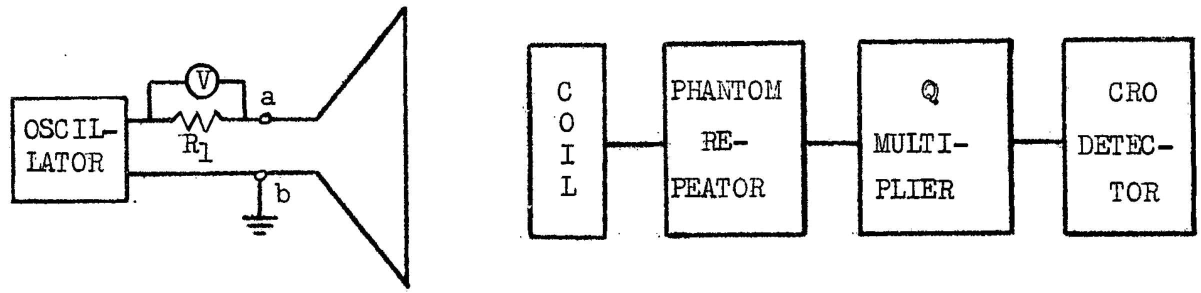

Fig. 3

The two types of shielding investigated are the ones most commonly used, and are based on the principle of providing a return path for the current such that it will produce a magnetic field equal and opposite to that of the "forward" current and thus cause partial cancellation of the total magnetic field external to the wire. The test set-up was arranged so that a pair of twisted leads, a bare wire, and a length of shielded cable (Belden #8401), could be alternately placed between points "a" and "b". An audio oscillator was used as a current source; the current being measured in terms of the voltage developed across R_1.

Both the oscillator and the resistor were kept far away from the search coil to prevent any extraneous pick-up from this source. The shielding ratio was then determined by measuring the current needed in the two types of shielded wire (alternately placed between "a" and "b") to provide an output voltage from the search coil equal to the voltage induced when the same current was passed through the bare wire located at the same place. The shielding ratio is then given by

$$R = \left.\frac{I_1}{I_2}\right]_{v_c\ =\ \text{constant}} \qquad (1)$$

where I_1 = the current in the shielded wire

I_2 = the current in the bare wire

v_c = the voltage induced in the search coil .

The shielding ratio as a function of frequency is shown in Fig. 1. The R for the Belden cable levels off to a value of approximately 800 above 7 kc, while the twisted pair drops close to zero in this frequency region. However, it is interesting to note that the twisted pair compares favorably with the shielded cable over a range of audio frequencies that is fairly large and quite important for the transmission of speech. The increase in R at the low frequencies is

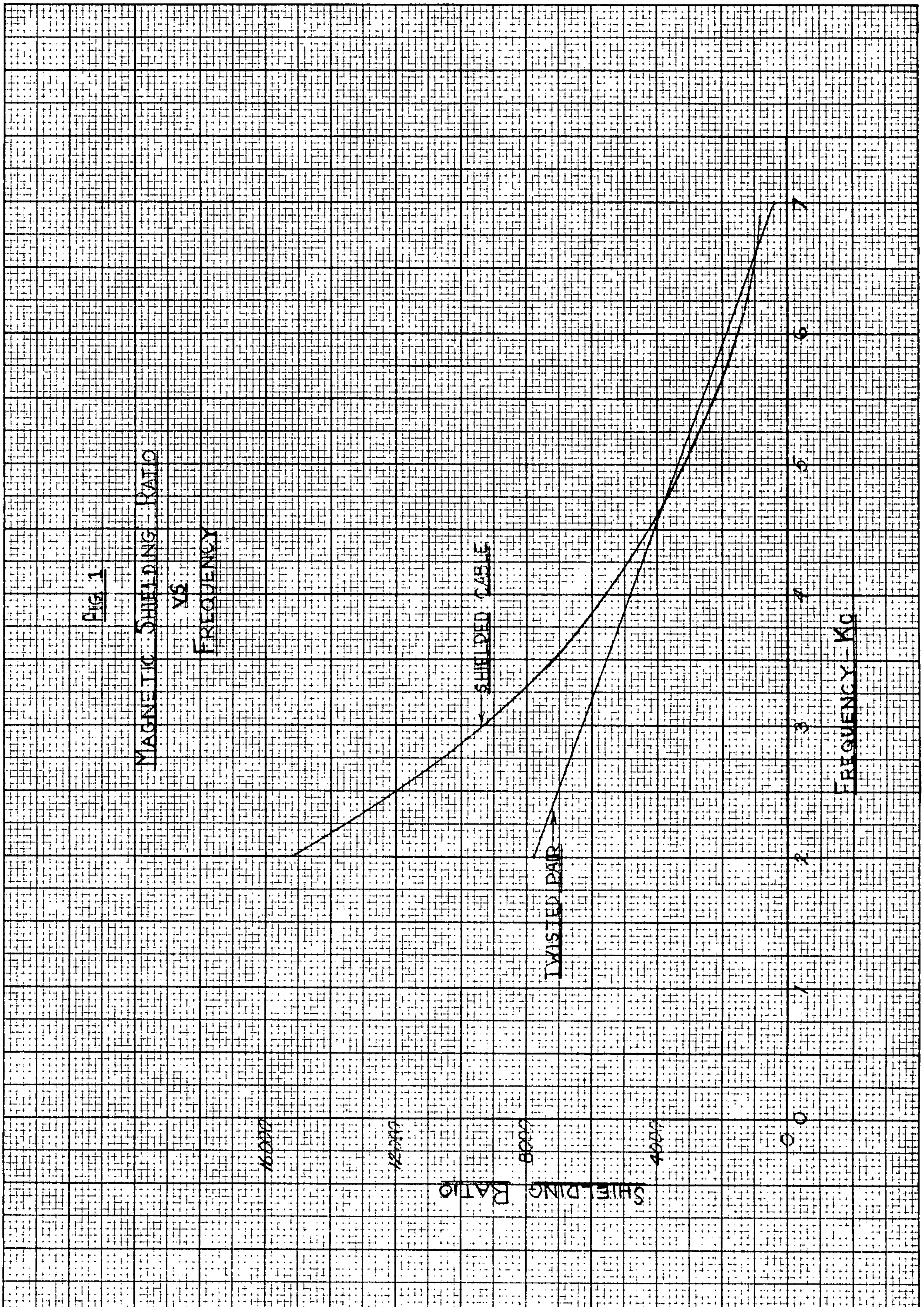
FIG. 1
MAGNETIC SHIELDING RATIO
VS
FREQUENCY
SHIELDED CABLE
TWISTED PAIR
SHIELDING RATIO
16000
12000
8000
4000
0
0
1
2
3
4
5
6
7
FREQUENCY – KC

probably due to the fact that physical differences in the two current paths of a shielded lead will affect the symmetry for relatively short wavelengths much more than for long ones, thus causing less effective field cancellation at the high frequencies.

The effectiveness of these two types of wire for shielding electric fields was also investigated by using them to shield a voltage as shown below:

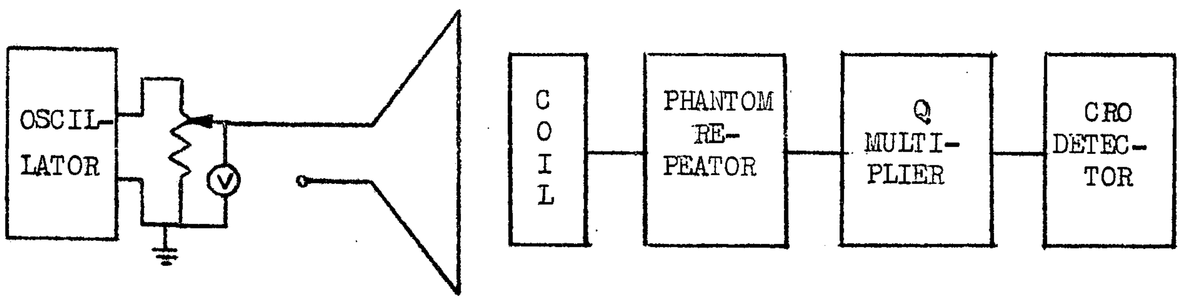

Fig. 4

The shielded cable (Belden #8401), with the shield at ground potential, was found to have a shielding ratio of about 20:1 throughout the frequency range indicated in Fig. 1. The twisted pair provided little or no shielding. The results are as expected since the first criterion for good electrostatic shielding is the surrounding of the field source by a ground plane.

The results of this test concerning magnetic shielding can be used to re-evaluate the search coil sensitivity requirements for the detection of the small currents produced by energized microphones. First, however, the effect of noise voltage in the coil must be reconsidered.

In the first progress report the following equation was derived:

$$B = \frac{180 \times 10^{-4}}{nA} \sqrt{\frac{L}{Q}}$$

where B = the smallest magnetic field that can be detected with a given coil
n = the number of turns
A = the average coil area in square inches
L = the coil inductance in henries .

This equation is based on certain assumptions which are as follows:

1. The limiting factor on sensitivity is the thermal noise in the coil.
2. The Q of the circuits associated with the coil is approximately 1000.
3. The required signal-to-noise ratio is 5:1.

Experimental work has since shown the second and third of these assumptions to be valid; however, as described in the second progress report, the noise voltage induced by electrical transients rather than the thermal noise voltage is the limiting factor on coil sensitivity. From curves of noise voltage vs. frequency (Second Progress Report - Fig. 1) the rms noise voltage for coil #2 at 4.5 kc is found to be 3.2 millivolts. These curves are repeated here in Fig. 2. Since coil #2 is one of the best search coils built to date, revised sensitivity calculations will be shown taking into account the higher noise level.

The noise due to thermal agitation is given by

$$E_n = .13\sqrt{ZB \times 10^{-6}} \text{ microvolts} \qquad (3)$$

$$Z = QX_L = 175 \times 2\pi \times 4.5 \times 10^3 \times 2.29$$

$$= 11.32 \text{ megohms}$$

$$B = \frac{f}{Q_c} = \frac{4.5 \times 10^3}{1000} = 4.5$$

$$E_n = .13\sqrt{11.32 \times 10^6 \times 4.5 \times 10^{-6}} = .928 \text{ microvolts} .$$

Since the actual noise voltage at this frequency is 3.2 millivolts, the loss in sensitivity due to this higher noise level is

$$S_L = \frac{3.2 \times 10^{-3}}{.928 \times 10^{-6}} = 3450 .$$

Equation (2) may be modified as follows:

$$B = S_L \frac{180 \times 10^{-4}}{nA}\sqrt{\frac{L}{Q}} \qquad (4)$$

for coil #2 at 4.5 kc:

$$B = \frac{3450 \times 180 \times 10^{-4}}{3000 \times 62.1}\sqrt{\frac{2.29}{175}} = 3.5 \times 10^{-7} \text{ gauss}$$

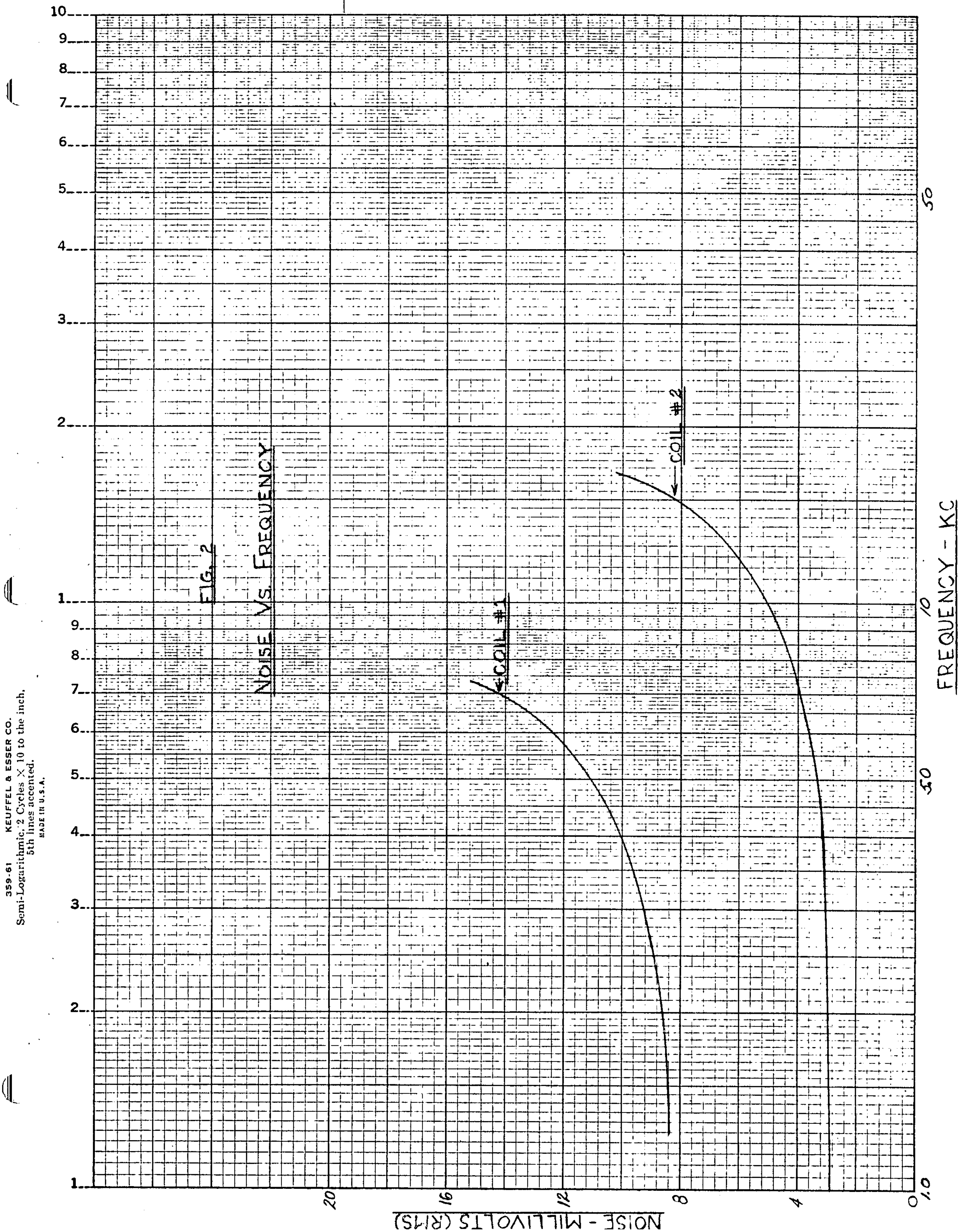
FIG. 2
NOISE VS. FREQUENCY
COIL #1
COIL #2
FREQUENCY - KC
NOISE - MILLIVOLTS (RMS)
1.0
10
50
20
16
12
8
4
0
359-61 KEUFFEL & ESSER CO.
Semi-Logarithmic, 2 Cycles × 10 to the inch.
5th lines accented.
MADE IN U.S.A.

where B is the smallest magnetic field detectable. This agrees reasonably well with the experimental value found for this coil (B = 4.0×10^{-8} gauss), if the effects of favorable orientation and stray signal current are considered. Previous work has shown that coil #2 is close to the ultimate in magnet wire coils designed for this purpose. The best Litz wire coil designed and built has a theoretical sensitivity of $B = 2.19 \times 10^{-7}$ gauss. An attempt to redesign these coils for lower noise is obviously futile due to the fact that the noise vs. frequency curves (Fig. 2) are practically constant in the region of operation and rise in the vicinity of the self-resonant frequency of the coil. The other factor affecting the noise voltage is the number of turns of wire wound on the coil. However, since both the noise voltage and the signal voltage are directly proportional to the number of turns, nothing is to be gained by manipulation of this factor. On this basis, it is reasonable to assume that a value of $B = 10^{-9}$ gauss at 4.5 kc is the best sensitivity that can be obtained with a tuned search coil of this type. The value of 10^{-9} gauss represents a coil whose sensitivity is 2.5 times better than any experimental result. An investigation will now be made of the feasibility of detecting microphone currents flowing in shielded cable with a search coil of this approximate sensitivity.

The magnetic field at a distance of r cm from a long, straight, current-carrying wire is given by

$$B = \mu H = (1) \frac{\sqrt{2}\, I_{rms}}{10\, r} \text{ gauss} \quad . \qquad (5)$$

Solving for the current,

$$I_{rms} = \frac{10\, Br}{\sqrt{2}} = 7.07\, Br \quad .$$

Assuming a coil sensitivity of 10^{-9} gauss as previously discussed and at a distance of 30 cm (about 1 ft.),

$$I_{rms} = 7.07 \times 10^{-9} \times 30 = .212 \text{ microamps} \quad .$$

This says that a current of .212 microamps or more flowing in an unshielded wire can be detected by this coil. From Fig. 1 it is seen that the shielding ratio at 4.5 kc for shielded cable is R = 3,400. The minimum current flowing in shielded cable that can be detected is therefore

$$I_{rms} = .212 \times 10^{-6} \times 3{,}400 = .72 \text{ milliamps} \quad .$$

This value is based on the assumption of a long straight wire. In the case of a microphone, it is not likely that the current source will meet this requirement. Therefore, this value of .72 milliamps must be accepted as the bare minimum of current that can be detected by this coil at 4.5 kc.

Upon examining various types of microphones, it is found that .72 milliamps is approximately one hundred times the current that can be expected from a crystal microphone, and ten times the current that can be expected from a low-impedance dynamic microphone when both are excited by high-level sound intensity. Therefore, it may be concluded that for crystal, dynamic, and other microphones having a similar range of current output, there is only a very slight possibility of detection by the type of search coil and associated circuitry heretofore described. The carbon microphone will supply from 10 to 15 milliamps of signal current when energized by high-intensity sound. However, the frequency characteristic of this type of microphone is such that the output begins to fall off between 3 and 3.5 kc. Therefore, when operating with this microphone, it is necessary to accept either the reduced output at the higher frequency, or lower coil sensitivity at the lower frequency. Experimental results with this type of microphone indicate that it is on the border line in so far as the possibility of detection is concerned. This seems to bear out the theoretical results if we assume 2 to 3 milliamps of signal current flowing in twisted pair at 4.5 kc. Since the shielding ratio of twisted pair is approximately the same as for the shielded cable at this frequency, the value of .72 milliamps is still a reasonable minimum criterion, and it is to be expected that detection is barely possible under these conditions.

Due to the unpropitious results obtained thus far with magnetic detection systems, an investigation into the possibility of an electric field detection system was begun. The possible use of such a system was indicated by the sensitivity of the search coils to minute alternating voltages at the system frequency. This type of detection, which is of interest for high-voltage low-current microphones, indicates the presence of an electric field due to the voltage at the output terminals of the transducer. This voltage is capacitively coupled to the input stage of the detection system as shown below in the physical drawing and the electrical analogue.

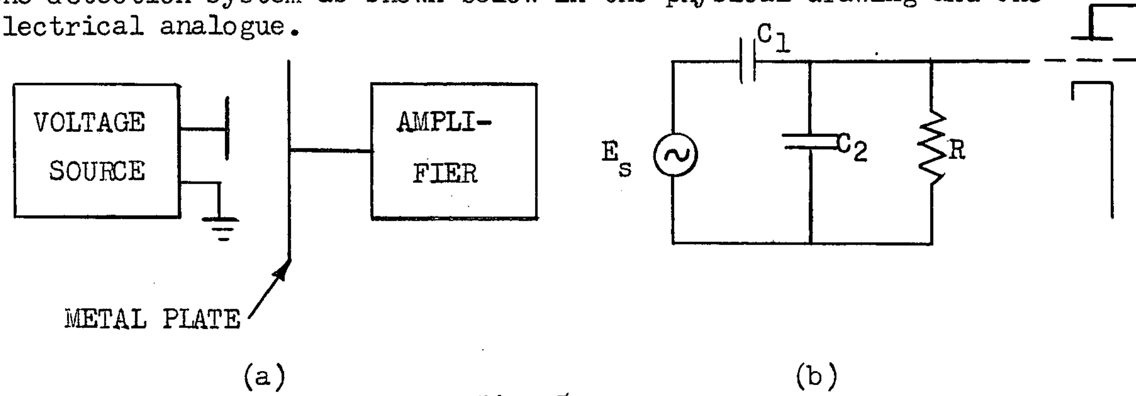

Fig. 5

The metal plate is a satisfactory pick-up for this purpose since its only function is to supply a conducting plane for the termination of the electric field. In Fig. (5b) C_1 represents the capacity coupling the voltage source, E_s, to the amplifier. C_2 represents the sum of the tube input capacity and the capacity of the metal plate to ground. At frequencies such that the input impedance of the tube is much greater than Xc_2, the input to the amplifier (voltage across R) is given by

$$E_{in} = E_s \frac{C_1}{C_1 + C_2} \quad . \tag{6}$$

Since C_1 is determined primarily by the area of the source, the area of the pick-up, and the distance between the two, it may be easily designed for a maximum. C_2, however, must be kept low by using a tube with a low input capacity and attempting to minimize the capacity of the pick-up to ground. Then, if C_2 is small, Xc_2 becomes quite large, and a tube with an input impedance of 100 to 200 megohms in the 2 to 4 kc range is required if the tube is not to have any shunting effect on Xc_2. An electrometer tube can be used to provide this high input impedance; however, a more satisfactory device is a feedback amplifier that will not only have a high input impedance, but will also compensate for a large part of its own input capacity, thus permitting a length of shielded cable at the input. The principle of operation of such a device is seen below.

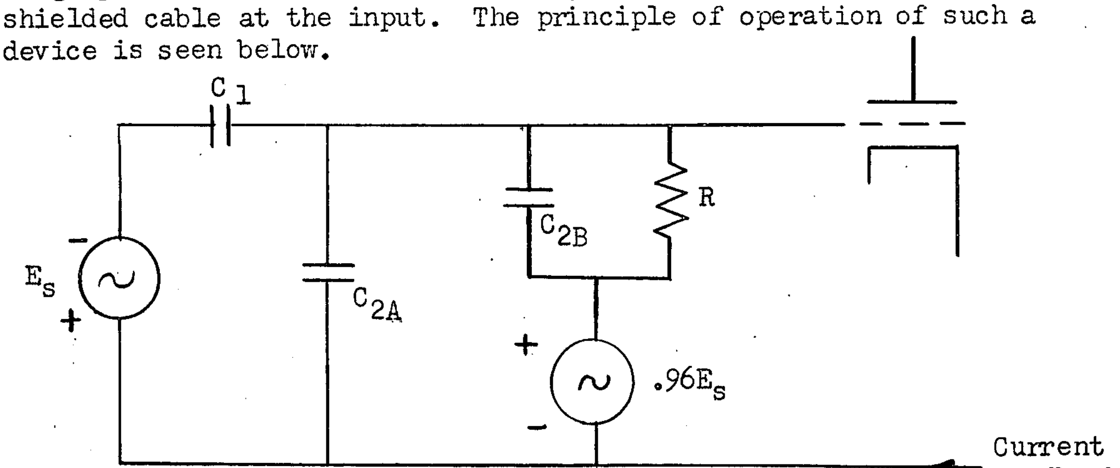

Fig. 6

C_1 represents the capacitive pick-up as before, C_{2A} is the capacity of the pick-up to ground, and C_{2B} is the input capacity of the tube and associated cable. Current is fed back 180° out of phase so that a voltage of about .96 E_s (and of opposite polarity) is developed as shown. Due to this, very little current flows through R and C_{2B}, thus presenting a high input impedance to the source. A commercial device of this type having an input impedance of 200 megohms shunted by 6 uuf was used in subsequent work.

Another important factor controlling the detection sensitivity is the signal-to-noise ratio. In this case, just as in the case of the search coil, the main source of noise will be external and not due to thermal agitation. That is, transient voltages in the vicinity of the metal plate will produce changing electric fields and introduce noise into the system. This noise is quite random in nature and is therefore difficult to filter effectively.

A complete system using the capacitive-coupling detection method was built and tested. The system is identical to the "self-oscillating system" discussed in the previous report except for the type of pick-up, which is a fine wire mesh that will not attenuate sound waves.

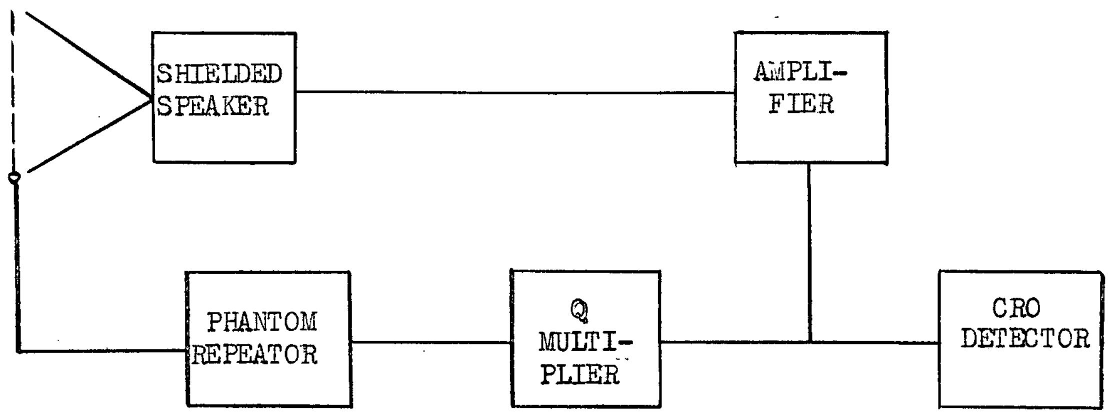

Fig. 7

Stray fields are picked up by the wire mesh, which is the input to the high impedance coupling unit (Phantom Repeater). The amplified noise is then fed to the narrow bandwidth Q multiplier, and the resulting single frequency (approximately) is amplified and used to energize the loudspeaker; thus noise voltage is converted to an almost pure audible frequency. If a microphone having sufficient voltage output is brought close to the mesh and energized by this sound, the electric field produced by the microphone output voltage will be picked up by the mesh and transmitted through the system.

This feedback continues until something in the system reaches saturation, as is indicated by the oscilloscope and by the increased output. This only occurs if the electric field emanating from the microphone is capacitively coupled to the wire mesh with sufficient magnitude to over-ride the noise being picked up.

When magnetic detection was used, it was found difficult to adequately shield the speaker when it was mounted near the coil. For electrostatic detection, however, shielding is very effective once the voltage source is surrounded by a ground plane. With this in mind, two types of pick-up were built as shown:

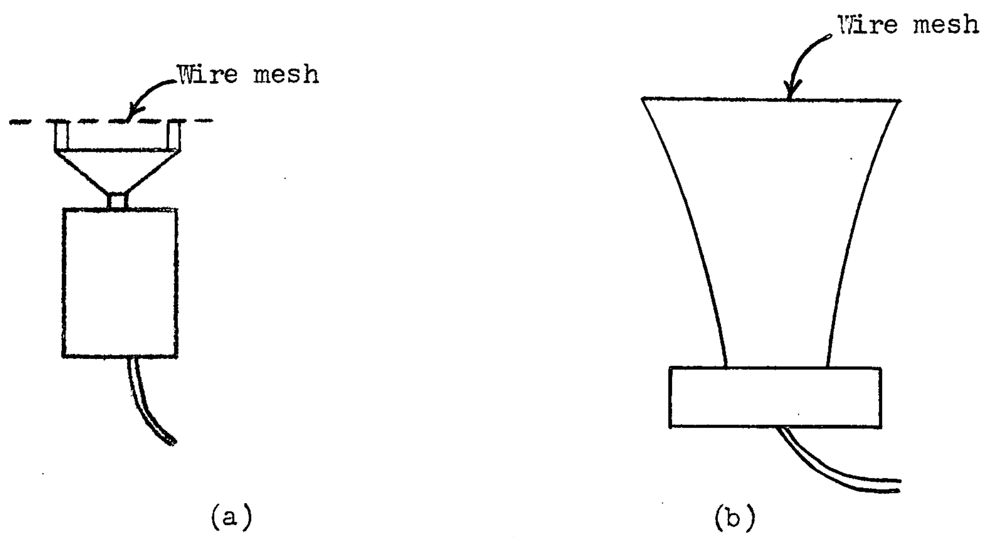

Fig. 8

Model (8a) utilizes a small "tweeter" whose driver unit is enclosed in a shielded can. A wire gauze mounted on the horn with insulators serves as the pick-up. Model (8b) utilizes a 2-ft horn-type speaker with a shielded driver unit. The wire mesh is fastened across the mouth of the horn, which is made of an insulating material. Model (8a) was used for high frequency tests, while Model (8b) was used in the low frequency range.

Initial tests showed that as a microphone approached the wire mesh detection occurred only at certain fixed distances which were found to be a function of the frequency of operation. This is due to the fact that the detection system will oscillate only when the speaker output due to noise and the speaker output due to the microphone are in phase. Since the phase of the input signal due to the microphone depends on the fraction of a wavelength that the microphone is separated from the mesh, detection occurs at one-wavelength intervals up to a distance where the microphone voltage output is insufficient. This means that there are fairly large spaces between points of detection at low frequencies (1 ft at 1 kc), which is not desirable. For this reason, and because of the fact that the ambient noise was slightly lower at the lower frequencies, an operating point of 2 kc was chosen.

Tests on the various types of microphones showed that the crystal microphone is the only type with sufficient voltage output to be detected by this system, provided the voltage source is not completely shielded by a ground plane. The crystal microphone can be detected with this system at distances up to 3 ft if either the connecting wires or the crystal element is unshielded. If everything is shielded except the point at which the microphone connects to the cable, detection can be accomplished at distances up to 6 in. If the crystal element, the connecting pins, and the cable are completely enclosed by a ground plane, the microphone cannot be detected with this system. Although experiments are continuing in an attempt to improve the system sensitivity, it is believed that its usefulness is severely limited by the effectiveness of electrostatic shielding.

In view of the sensitivity limitations caused by the high ambient noise level for both magnetic and electric field detection, it is felt that techniques more suitable for the detection of a small signal in the presence of excessive noise should be utilized. This involves sampling operations whereby certain characteristics of the signal are compared to a reference in such a manner as to remove the effect of the noise which does not possess these certain characteristics. Also, thought has been given to the possibility of modifying a "mine-detector"-type unit (upon receipt of same) in an attempt to improve its sensitivity.

IV. SUMMARY:

1. An investigation has been made into the shielding effectiveness of "twisted pair" and shielded microphone cable. These results, in conjunction with the previous data on ambient noise, have been used to re-evaluate the search coil sensitivity needed to detect microphone current in shielded cable. It is shown that the present magnetic detection system has little promise except in the case of a high-current carbon microphone.

2. Work on electrostatic detection has led to a system whereby a crystal microphone may be detected at distances up to 3 ft, depending on the amount of shielding used on the microphone and associated cable. As yet the system is completely insensitive to microphone current that is completely enclosed by a ground plane.

V. FUTURE PROGRAM:

1. The present magnetic and electrostatic detection systems will be

reviewed in an attempt to introduce modifications designed to negate the effects of excessive ambient noise. Various sampling and coincidence techniques will be considered.

2. An attempt will be made to modify a mine-detector-type unit so as to improve its sensitivity for detection of metallic and non-metallic (unshielded) microphones.

VI. PERSONNEL:

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[redacted]	Project Manager Specialist Engineer Technician Technician

VII. MEETINGS AND CONFERENCES:

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[redacted]

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Submitted by: [redacted]

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Approved by: [redacted]